

Microplasticity and High Ductility During Microtensile Testing of Free-Standing Aluminum Films

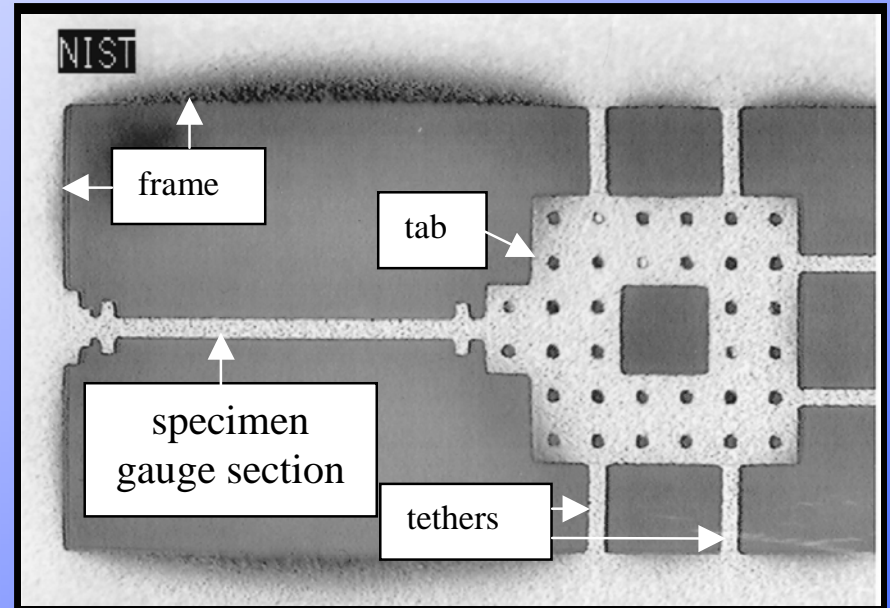
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Thin Film Ductility

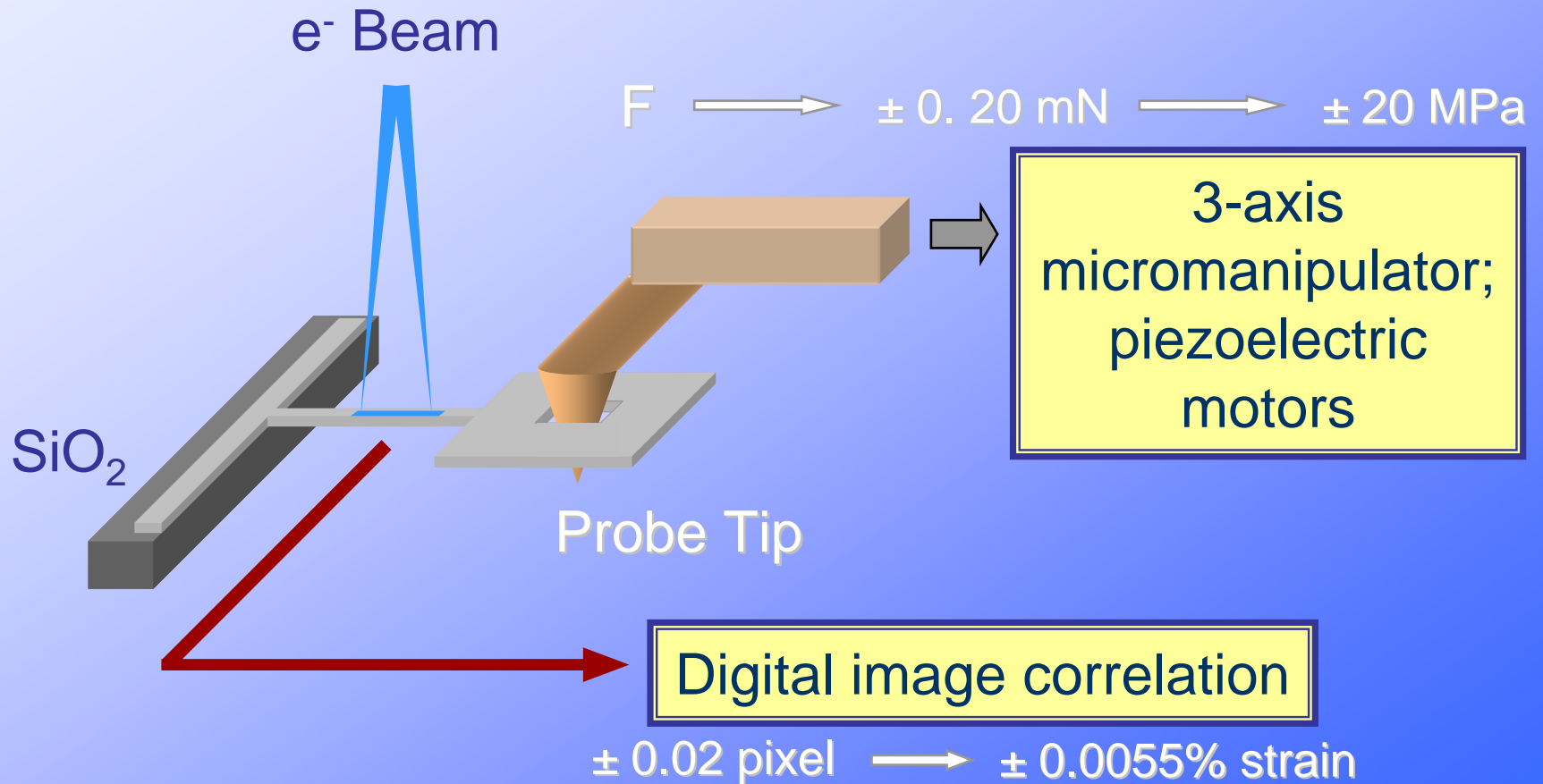
- Affected by: fine grain size, film dimensions
 - scaling effects are important since microplasticity exhibits characteristic dimensions (cells, PSBs, etc.)
- Measured by: microtensile tests on free-standing films or films on elastic substrates, bulge tests
 - other test methods do not provide information about elongation

Specimens

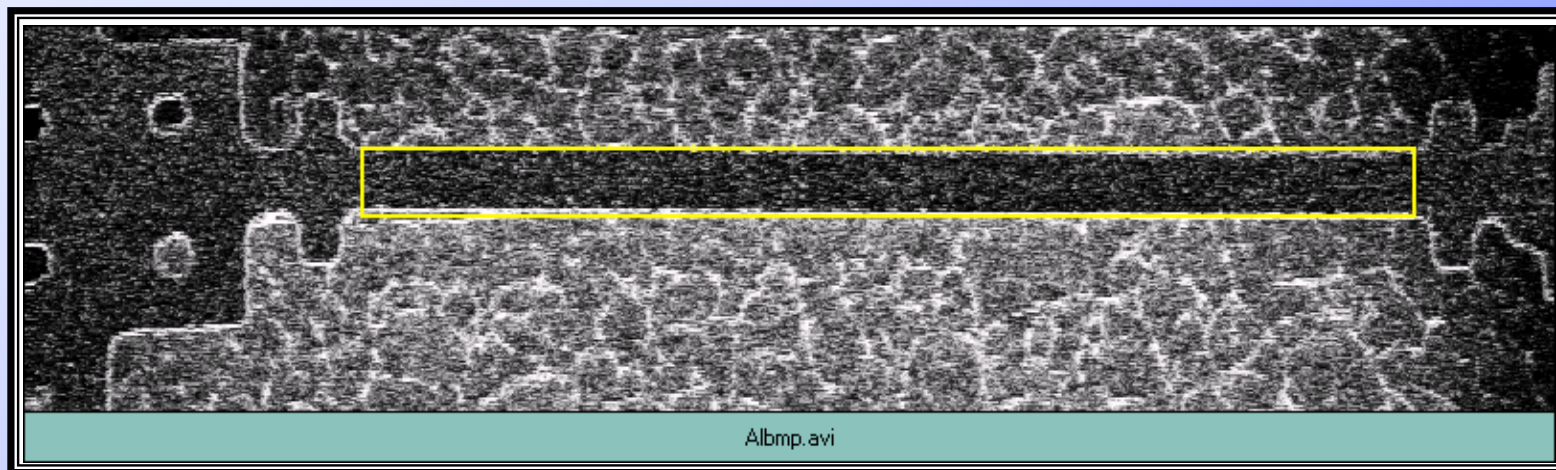
- Pure Al, e-beam deposited onto bare Si
- Si etched away using XeF_2 , leaving free-standing Al
- Gauge section:
 $10\ \mu\text{m} \times 180\ \mu\text{m} \times 1\ \mu\text{m}$



Microtensile Test in SEM



What We See



20 μm

SEM image sequence taken over 3 minutes.

$$\dot{x} = 0.3 \mu\text{m} / \text{s}$$

$$\epsilon \sim 30\%$$

Mechanical Properties

6 Tests:

Ductility

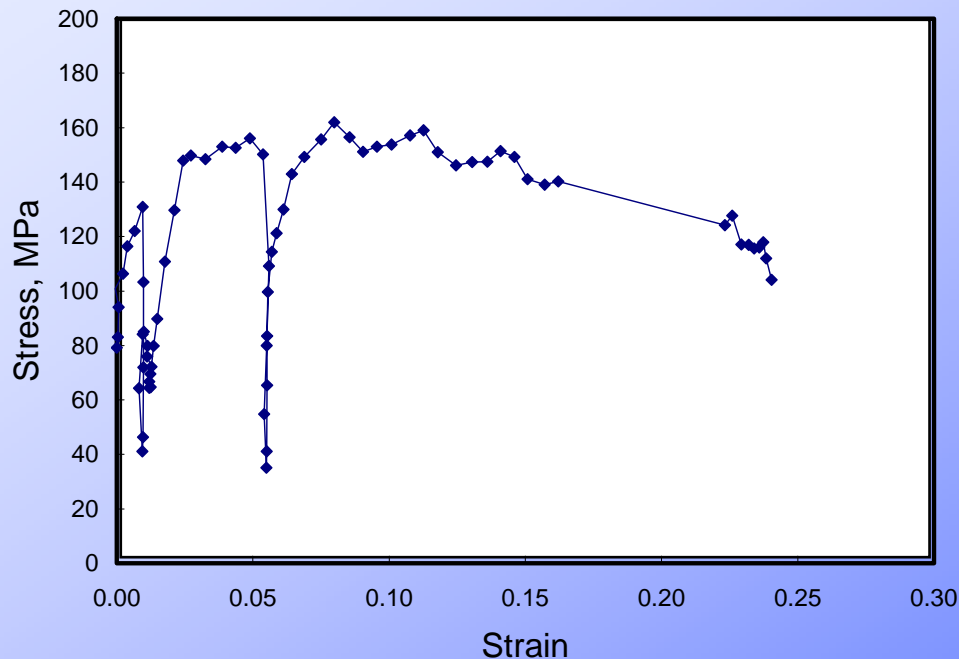
- Mean: 22.5%
- Range: 13 - 32
- Std. Dev.: 5.0

0.2% Offset σ_{ys}

- Mean: 93.8 MPa
- Range: 87 - 105
- Std. Dev.: 10.1

UTS

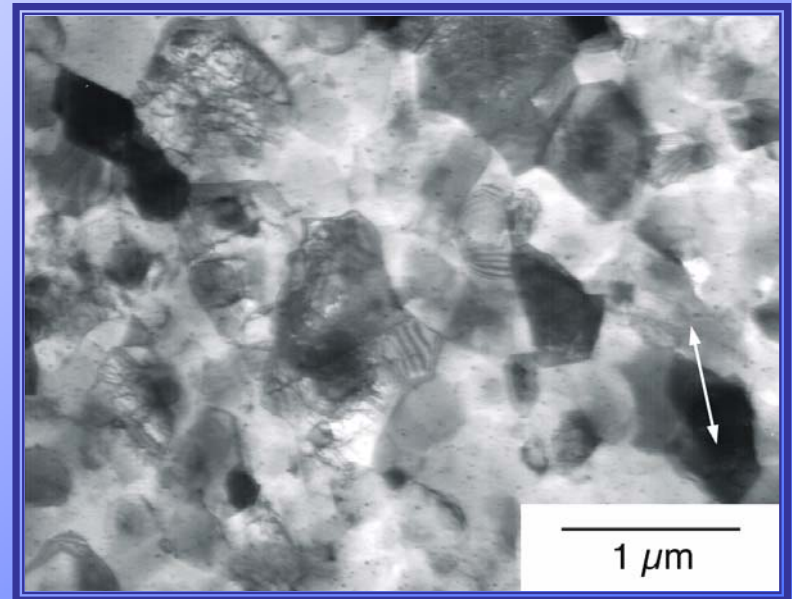
- Mean: 151.0 MPa
- Range: 124 - 176
- Std. Dev.: 19.8



Microstructure by TEM

Can observe films without thinning

- 0.3 μm grain size
- Few dislocations have accumulated, even after fracture
- No information on texture or deposition stresses



Al film strained to ~ 24%;
Image from uniform deformation region.

High Ductility and Uniform Deformation

- High strain rate sensitivity exponent, m , ~ 0.20 :

$$\sigma = C \dot{\varepsilon}^m$$

Other thin film tests: compare $> 40\%$ for $m = 0.26$ and $\sim 3\%$ for $m = 0.1$

$$dA / dt = (1 / C') F^{(1/m)} (1 / A^{\frac{1-m}{m}})$$

Area reduction occurs more slowly for higher m .

- High strain hardening coefficient, n , ~ 0.12 :

$$\sigma = K \varepsilon^n$$

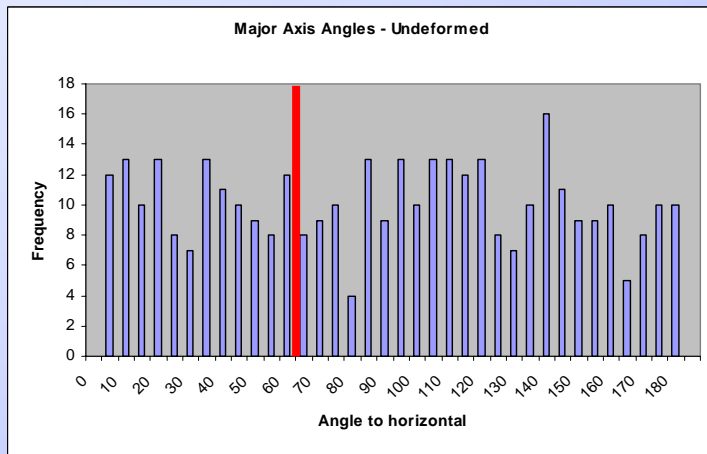
Uniform strain until $\varepsilon_t = n$.

Necked area strengthens more, adds to strain rate effect, “spreading” the strain.

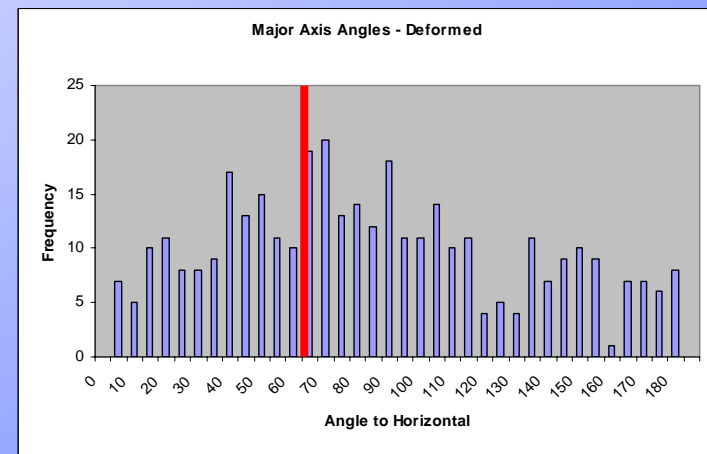
These properties promote more uniform deformation.

What About Dislocations?

Grain shapes by TEM: 350 - 400 grains/sample



As-Deposited



Deformed

Plastic compatibility must be maintained, otherwise grains 'overlap' or show voiding at boundaries.

Can use geometrically-necessary dislocations to accommodate strain.

How Many Dislocations?

$$\bar{\varepsilon} = \frac{\delta l}{l} = Nb / d$$

total strain in one average grain, to maintain compatibility

$$\rho_G = N / \text{area}_{\text{grain}} = \frac{\bar{\varepsilon} d}{b \cdot \text{area}_{\text{grain}}}$$

N = number of dislocations to cause displacement

$$\bar{\varepsilon} = 0.24$$

$$b = \text{Burgers Vector} = 2.86 \cdot 10^{-8} \text{ cm}$$

$$d = \text{average grain diameter} = 0.3 \cdot 10^{-4} \text{ cm}$$

$$\text{area}_{\text{grain}} = \pi d^2 / 4$$

$$\Rightarrow \rho_G = 3.56 \cdot 10^{11} / \text{cm}^2 (= 3560 / \mu\text{m}^2)$$

$$\rho_G \cdot \text{volume}_{\text{grain}} = 160 \mu\text{m} = \text{total line length to give } \varepsilon = 24\%$$

$$\longrightarrow \sim 500 / \text{test}$$

For a 500 s test, can we get 1 dislocation/s ($v \sim 0.3 \mu\text{m/s}$)?

Summary

- Microtensile tests on free-standing Al within SEM
- Ductilities averaging $> 20\%$
- Pronounced strain rate effect: necking delayed
- Simple concepts of geometrically-necessary dislocations may be able to account for high elongation